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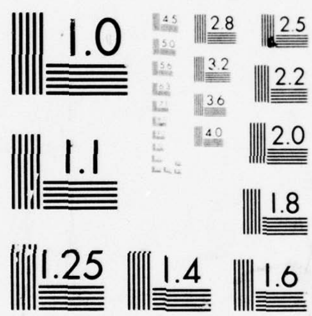

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REPORT 77-4

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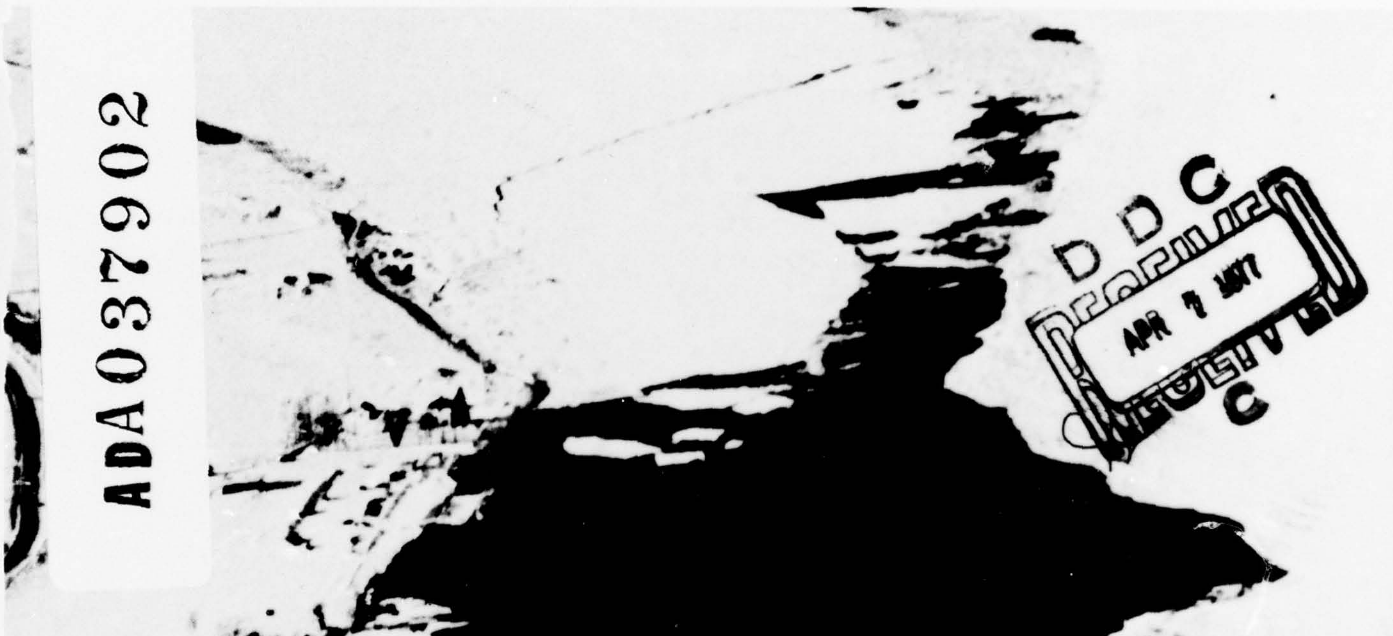
St. Marys River ice booms

Design force estimate and field measurements



Cover: Ore carrier Presque Isle *passes through ice boom on St. Marys River at the outlet of Sault Ste. Marie Harbor. The boom is about one ship length astern of the 1000-ft-long ore carrier. (Photograph by U.S. Army Engineer District, Detroit.)*

CRREL Report 77-4

St. Marys River ice booms

Design force estimate and field measurements

Roscoe E. Perham

February 1977

Prepared for
U.S. ARMY ENGINEER DISTRICT, DETROIT
By
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A set of two ice booms with a 250-ft (76-m)-wide navigation opening between them was designed to stabilize the ice cover in the harbor at Sault Ste. Marie, Michigan and Ontario, and to reduce the ice losses associated with winter navigation of ships on the St. Marys River. The forces from natural effects on the ice cover were predicted using existing theory and physical data for the area. The forces in the boom structure resulting from ice cover and boom interaction were estimated. When the ice booms were installed, force measurement systems were put into selected anchor cables. These systems were operated all winter in conjunction with a modest program of supplemental data gathering. The force data exhibited periods when the force distribution was in good agreement with predictions and periods when the effect of ice on the booms differed substantially from predictions. Sometimes passing ships

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had a substantial effect on the ice cover and the boom loads, and at other times, the effect was negligible. The direction of travel made little difference on average peak loads. The maximum loads on the booms resulted from natural occurrences.

PREFACE

This report was prepared by Roscoe E. Perham, Mechanical Engineer, Northern Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

The work described in this report was funded by the U.S. Army Engineer District, Detroit, Michigan, under FY 76, USAED, Detroit Order No. NCE-IA-76-129, *St. Marys Ice Boom Instrumentation*. USA CRREL is responsible for the ice engineering portion of this program.

The technical content of this report was reviewed by Dr. D.E. Nevel and Dr. G.D. Ashton of USA CRREL; their efforts are appreciated.

USA CRREL worked with the Detroit District in the design of the ice boom and provided the force measurement systems which were operated throughout the winter of 1975-1976.

The efforts and cooperation of many individuals and organizations were needed for the success of the St. Marys River ice booms this past winter. Hydro-Quebec of Canada was generous in providing information about their ice booms to the Detroit District. Acres American, Inc. made the model tests. The ice booms were built and installed by the Durocher Dock and Dredge Company of Cheboygan, Michigan, under the supervision of the Soo (Sault Ste. Marie, Michigan) Area Office. Personnel from the Soo Area Office monitored the recorder equipment throughout the winter and kept the accompanying log book and notes.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

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SUMMARY

As an aid to winter navigation, two ice booms with a 250-ft (76-m)-wide navigation opening between them were installed at the outlet of the harbor at Sault Ste. Marie, Michigan and Ontario, to stabilize the ice cover in the harbor during the winter of 1975-76. The location and lengths of these booms were determined previously by model tests seeking to minimize harbor ice losses due to passing ships. The construction details for the booms were taken care of separately from the work reported here.

The forces on the ice due to natural phenomena such as water and wind drag, gravity, and waterway and ice interaction were calculated using predictive relationships from available literature and physical data about the harbor. The force distributions in the ice booms were based on unconsolidated ice cover theory. The maximum load in the west ice boom was expected to be 73,000 lbf (325 kN) and that in the east ice boom, 45,000 lbf (200 kN). The effect of passing ships was an unknown factor.

Forces in the upstream end of the ice boom structure were monitored continuously throughout the winter by six underwater sensors in the structure, i.e., 3 in each boom. Forces were recorded in a log book and on chart paper. Supplemental data on ship passages, ice conditions, meteorological conditions, waterflow and water levels were also taken.

The force data were analyzed and it was found that in early winter, when the ice cover was wholly fragmented, the force distribution in the structure was as expected based on theory and was lower than the maximums predicted. Later in the winter the ice moved as a large solid or partially broken sheet and applied heavy loads to some point on the ice booms, usually the flotation buoys. The forces then were sometimes greater than expected and once were as high as 97,000 lbf (431 kN). The effect of momentum in an ice cover was noticed.

The maximum forces in the boom were the result of natural phenomena, but the effect of thermal effluents and ships in the harbor contributed to the conditions. Often the passing ships had a noticeable effect on the forces being registered and often they did not. Under some circumstances, the effect of minor disturbances such as the bow wave registered. A main finding was that the ships had nearly the same effect when upbound through the booms and ice cover as they did when downbound. The average peak force occurring during ship passages was approximately 25,000 lbf (111 kN). The size of the ship and the way it was operated (power level, perhaps) also affected the peak force, although no forces were higher than the expected loads. The ships seemed to have a substantial effect on the water levels and flows in and near the navigation channel and to let the natural forces present in the cover act on the booms.

ST. MARYS RIVER ICE BOOMS – DESIGN FORCE ESTIMATE AND FIELD MEASUREMENTS

Roscoe E. Perham

INTRODUCTION

The St. Marys River is the natural waterway connecting Lake Superior with Lake Huron and one of the key links in the Great Lakes – St. Lawrence River Seaway. Both the United States and Canada have made a considerable investment to modify the river in the Sault Ste. Marie area for ship traffic. Besides building several locks and a powerhouse there, the United States has constructed the Little Rapids Cut, which is a 600-ft-wide shortcut passing between Sugar Island and the mainland. Recent experiences with ship traffic through this cut in the winter show that normal travel and commerce between the island and the mainland can be adversely affected by broken ice. The ice floats into the cut from the broad harbor of Sault Ste. Marie (Soo), Michigan, causing jams, blocking ferry operations, and raising the powerplant tailrace water levels too high. Normal conditions are shown in Figure 1. Figure 2 shows broken ice on the ferry route.

Model studies (Acres American, Inc. 1975) were made of this problem and one of the most promising solutions was a set of two ice booms with an opening

Figure 1. Normal traffic at Little Rapids Cut, St. Marys River, Michigan.

Figure 2. Ferry-stopping ice being cleared by U.S. Coast Guard icebreaker.

Figure 3. St. Marys River ice booms, showing boom shape (scalloped ice pattern to left and right of center) due to fragmented ice cover, 13 January 1976.

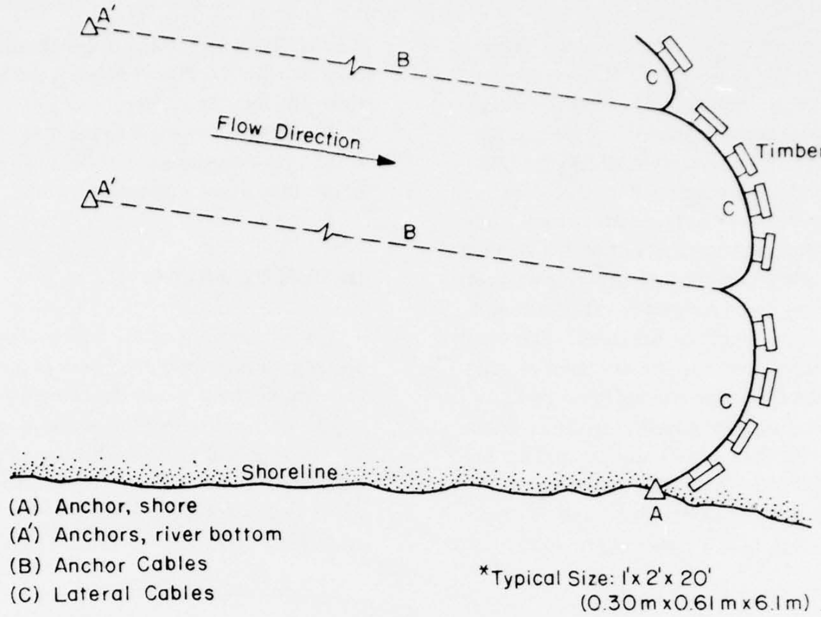


Figure 4. General ice boom features.

between them to allow ship passage while they performed their usual function of stabilizing and holding back the upstream ice cover.

This report describes the ice forces predicted by the design of the ice booms and reports the forces measured in the booms during the winter of 1975-76 at Sault Ste. Marie, Michigan. Figure 3 is an aerial photograph of the installed ice booms taken on 13 January 1976.

ICE BOOM BASIC PRINCIPLES

The ice boom is a series of floating elements such as timbers or pontoons which form a barrier across a body of water for the purpose of stopping moving ice floes. Ice booms are generally used on rivers and assist nature in forming a solid, stable ice cover. This cover reduces the area of open water present on the river during winter and consequently reduces the amounts of frazil ice and anchor ice that nucleate in the open water.

This floating barrier is held in place by a wire rope or a cable structure and anchors, as shown in Figure 4. Some of the cables follow the general line of the barrier, and the timbers or pontoons are connected to them by chains. Other cables, called anchor cables, connect these lateral cables to the anchors and serve to distribute the load on the ice boom. The structure is very flexible and often adjusts its shape in response to a load concentration.

GENERAL LOADING CONSIDERATIONS

The load on an ice boom in early winter comes from the ice floes that are collecting upstream of the floating barrier, as shown in Figure 3, especially to the right of center. The ice cover that is forming in this manner is called unconsolidated or fragmented. Later, the pieces freeze together into a sheet of ice which is then called solid.

Relationships were developed by Pariset and Hausser (1961) for predicting the loads that waterflow and gravity apply to the ice boom. Their analysis also considered the restraining friction force from river banks on the unconsolidated ice cover and used findings from earlier studies by Latyshenkov (1946) of forces on booms due to ice floes and by Kennedy (1958) of those due to logs.

The drag force of wind on an ice cover also was considered important by Pariset et al. (1966), and Michel (1968) suggested using the Karmen-Prandtl relationship for turbulent flow over rough surfaces to determine this force. However, the difficulty here is that a value for roughness height must be assumed. Siefert and Langleben (1972) seem to have come closest to resolving this problem by determining the dimensionless drag coefficient for winds over sea ice.

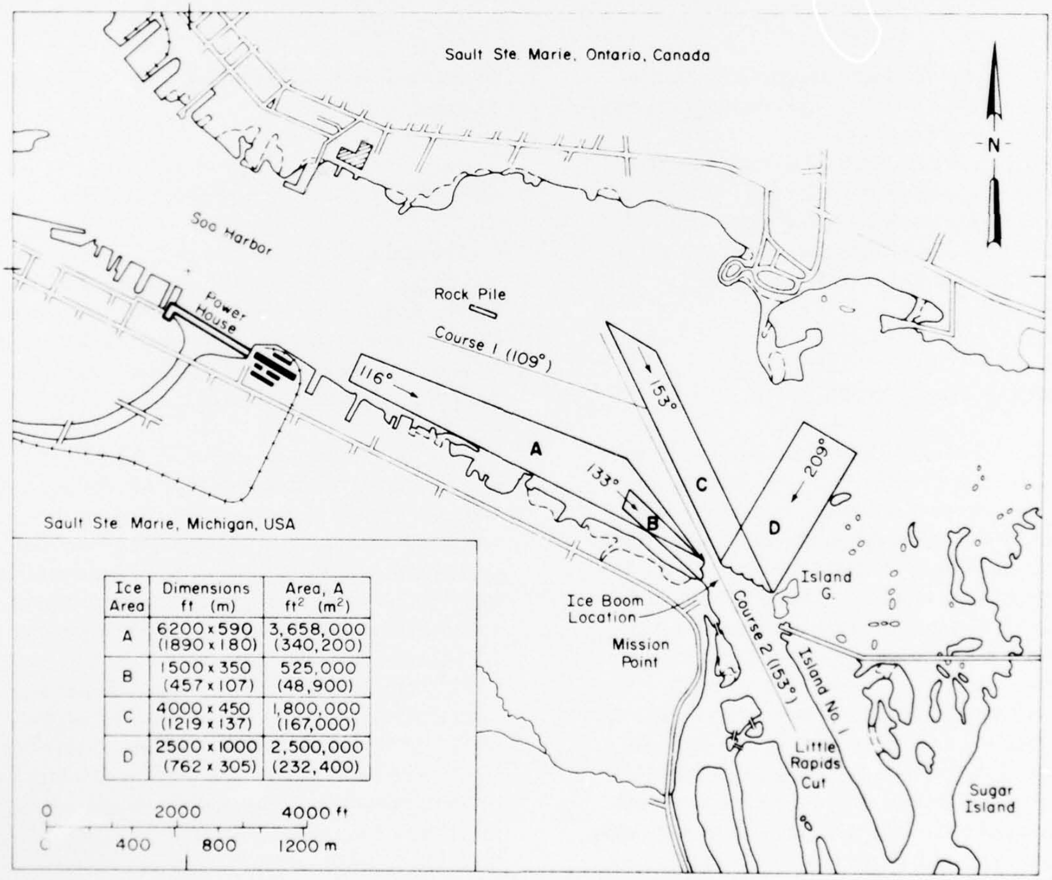
The response of ice booms to these forces depends considerably upon the ability of the floating ice barrier elements, such as timbers and pontoons, to hold back the ice. Under some conditions ice goes under these floating devices, but usually it slides over them.

The stresses and loads developed in various parts of an ice boom depend not only on the natural forces and the ice barrier characteristics, but on the geometry of the structure and its orientation with respect to the river flow or driving force directions. The geometry of the structure is the length of the lateral cables with respect to the anchor spacings, the direction of pull of the anchor cables, and the spacing between the anchors. For instance, a long section of an ice boom holds back more ice than a short section, and consequently receives a larger force than the latter.

The orientation of the ice boom, on the other hand, is the direction that the general line of the ice boom takes with respect to the shoreline or the direction of waterflow. If the ice boom is perpendicular to the flow, the same force level would be expected at each end. If it were set at an angle to the flow, however, a larger force would be expected at the upstream end of the boom than at the downstream end.

DESIGN ICE AREAS

Certain portions of the harbor ice cover are rationalized as acting upon one boom or another. The newly forming ice floes follow the current and are carried into the ice boom where they collect, as demonstrated by the small southwest harbor ice area (area B) and the downstream end of the northwest harbor ice area (area C), shown in Figure 5. The early ice cover formation is a collection of unconsolidated ice floes, or a



Ice Area	Dimensions ft (m)	Area, A ft² (m²)
A	6200 x 590 (1890 x 180)	3,658,000 (340,200)
B	1500 x 350 (457 x 107)	525,000 (48,900)
C	4000 x 450 (1219 x 137)	1,800,000 (167,000)
D	2500 x 1000 (762 x 305)	2,500,000 (232,400)

Figure 5. Soo Harbor and design ice areas.

fragmented ice cover. Later, the ice covers become solid and substantially larger, like those in the southwest harbor (area A) and the northeast harbor (area D) ice areas. A combination of severe weather conditions is required to have these large areas break loose from shore and act on the ice boom, and previous experience indicates that this sometimes happens. The ice areas and the estimated direction of their forces on the respective ice booms are shown in Figure 5.

PREDICTION OF ICE BOOM LOADS

Summary

The long-term loads on an ice boom are expected to come from natural forces acting on the ice which is being held back by the boom. These are the drag of water flowing under the ice, the drag of wind blowing over the ice, the push of water at the upstream edge of the ice, and the force of gravity tending to make the ice slide down the hydraulic slope.

The shoreline also affects the loads on the ice boom in that it acts against the push of the unconsolidated ice cover to prevent its spreading out laterally. In doing this, however, it also provides a force component which acts against the downstream push of the ice cover. Latyshenkov (1946) estimated that, in a regular-shaped channel, a cover of sufficient length can support itself by internal friction without being frozen to the shore. The passage of ships is expected to cause only short-term effects.

Ice Cover Forces

Main factors

The itemization of forces by Berdennikov (1964) seems to be the simplest start towards explaining the forces generated in a broken ice field or cover. The individual factors are listed and are subsequently eliminated or expanded according to whether or not they apply to the particular problem. Although Berdennikov analyzed the push of broken ice against the upstream edge of an ice cover, his analysis also applies to an ice boom.

The interactions of the ice cover, the river banks and the ice boom can generally be defined by a force balance in the longitudinal direction in the form

$$P_m + W + P_v + Q_i + F_v - P_s - T = 0 \qquad (1)$$

where P_m = thrust against the ice cover from moving ice from upstream

W = friction force of the wind

P_v = total hydrodynamic force against the upstream edge of the ice cover

Q_i = weight component of the ice masses parallel to the water surface and proportional to the slope of the water surface

F_v = friction force of the water under the ice cover

P_s = longitudinal component of the load-carrying forces of the boom cable

T = tangential force component caused by the friction of the ice against the river banks.

Shore effect

The shoreline of Soo Harbor, Saulte Ste. Marie, Michigan, may have little effect in holding back the fragmented ice because the harbor is much wider than the ice boom and the river flow is split in two directions. More importantly, the central part of any bridging-across by the ice in this area would periodically be broken by passing ships. Thus, for these calculations, the effect of the interaction of the ice and the shore T was considered negligible.

Gravity force

The gravity force Q_i is the downstream component of the weight of the ice cover floating on the sloping surface of the river; when the hydraulic slope is small, this component is small too. The southwest harbor ice area has a maximum slope of 2.23×10^{-5}. When the ice is 6 in. (0.15 m) thick, the area applies a distributed load of 8.3 lbf/ft (1.21 N/m) to the west ice boom. This value seems small enough to be neglected.

Form drag

The hydrodynamic force on the upstream edge of the ice cover P_v generally decreases as the ice cover progresses into the harbor from the ice booms because of a gradual decrease in the water velocity. Pariset and Hausser (1961) suggest a method of calculating this force which assumes that the thickness of the front of the cover is related to the velocity of the water flowing beneath it. Using their method, and an under-ice velocity of 2.5 ft/s (0.762 m/s), the drag equals 1.74 lbf/ft (25.4 N/m). This value is representative of a maximum expected value for the ice cover in the unconsolidated state and can be neglected.

Ice floe impact

When ice first forms against the boom, the floes are not massive. Later, as the upstream edge of the

cover moves up into wider parts of the harbor, the floes move more slowly. This lack of size and speed makes the impact force negligible here.

Water friction force

Stress calculations. The water friction analysis was simplified by assuming that the ice cover and the river bottom had the same roughness and that a representative value of drag or shear stress τ_0 would be applied to each ice area. The relationships used by Pariset and Hausser (1961) for determining this stress were used here. These relationships were developed for flows on ice-covered rivers and channels as follows:

$$\tau_0 = \rho g \frac{V_u^2}{C^2} \quad \text{lbf/ft}^2 \ (\text{N/m}^2) \qquad (2)$$

where ρ = mass density of water
g = gravitational constant
V_u = mean velocity of water under the ice
C = Chézy flow coefficient.

The Chézy flow coefficient C is proportional to the hydraulic radius R_h of the river or channel according to the following relationship:

$$C = KR_h^{1/6} \ \sqrt{\text{ft/s (m/s)}} \qquad (3)$$

where K ft$^{1/3}$/s (m$^{1/3}$/s) is a constant of proportionality.

In their report on the formation of ice covers and jams in rivers, Pariset et al. (1966) give representative values of $25 < K < 30$ ft$^{1/3}$/s for K during the initial ice formation period and $35 < K < 45$ ft$^{1/3}$/s for K later under the solid ice cover.

The Soo Harbor has a natural water depth of less than 10-ft (3.0-m) average and a dredged channel depth of about 28 ft (8.5 m) below low water datum (International Great Lakes Datum 1955). Each depth category composes about one-half the total harbor area. These depths were averaged and used with the minimum value of K during the ice formation period. The hydraulic radius was assumed to equal one-half the water depth. Assuming that V_u = 1.0 ft/s (0.305 m/s)

$$\tau_0 = 0.044 \ \text{lbf/ft}^2 \ (2.11 \ \text{N/m}^2).$$

The drag at the locations of particular booms was calculated using the water velocities and depths associated with the ice areas retained by these booms. This information was provided by the U.S. Army Engineer District, Detroit, and was based on drogue studies and a river flow of 86,000 ft^3/s (2435 m^3/s). Figure A1, App. A, gives representative information.

Force calculations. The velocity information was fortunately based on actual field measurements and a simple calculation procedure seemed best for determining the effect of the force of this parameter on the cover. Each major area was considered to be composed of several smaller portions and each of these had its own mean velocity, which was estimated by careful inspection of the field data. A shear stress was calculated for each portion using the previous equation, and the values obtained were then changed to their force equivalents by multiplying them by the size of their respective areas.

The components of each of the forces were then appropriately summed vectorially to determine the total force F_v for each major area. The value of distributed load due to water for an ice area was the force F_v divided by the span of the ice boom; the span is defined in Figure 6.

Wind drag

Wind blowing over an ice cover causes a tangential force on the cover. This effect is commonly referred to as wind shear stress τ and is most conveniently described in terms of a dimensionless drag coefficient C_d as

$$\tau = C_d \rho U^2 \quad \text{lbf/ft}^2 \ (\text{N/m}^2) \qquad (4)$$

where U = wind velocity referred to the standard meteorological height of 10 m, ft/s (m/s)
ρ = mass density of air, slugs/ft^3 (kg/m^3).

In their studies of wind shear over sea ice, Siefert and Langleben (1972) determined median values of 1.7×10^{-3} and 2.2×10^{-3} for C_d with a probable high value of 3.0×10^{-3}.

The second value of C_d was used here with eq 4 to calculate the wind drag. The wind velocity was assumed to be 50 mph, or 73 ft/s (22.2 m/s), along the line of force action (see Fig. 5) of each design ice area. Also assumed was an air density of 2.57×10^{-3} slugs/ft^3 (1.32 kg/m^3), corresponding to sea level pressure and an air temperature of 20°F (−6.7°C). Therefore,

$$\tau = 0.030 \ \text{lbf/ft}^2 (1.46 \ \text{N/m}^2).$$

The resultant force on the design area was then calculated and put into distributed load terms by dividing this value by the span of the ice boom.

Table I. Summary of loads from design ice areas.

		Distributed loads							
		Wind		*Water*		*Total*		*Total forces on ice area F_x*	
Ref.	*Ice area*	*(lbf/ft)*	*(kN/m)*	*(lbf/ft)*	*(kN/m)*	*(lbf/ft)*	*(kN/m)*	*(kips)*	*(kN)*
B	Little southwest harbor	79	1.15	46	0.67	125	1.82	34.4	153
A	Southwest harbor	251	3.66	370	5.40	621	9.06	211	939
C	Northwest harbor	122	1.78	492	7.18	614	8.96	245	1090
D	Northeast harbor	76	1.11	11	0.16	87	1.27	86	383
E*	Timber capability					130	1.90	52	231

	Load on individual boom sections													
	W1		*W2*		*E1*		*E2*		*E3*		*E4*		*E5*	
Ref.	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*
B	17.4	77	17	76										
A	94	418	117	520										
C					57	254	6	267	5	222	42	187	36	160
D					17	76	23	102	21	93	18	80	7	
E	26	116	26	116	26	116	26	116	26	116	26	116	26	116

* E is not an area.

Ice area load summary

The loads on the ice booms in the ice areas due to natural causes are shown in Table I. They are given in three ways: as a distributed load from each design ice area, as a total load on each design area, and as a total load on each ice boom section. The distributed load values were used for determining the loads in the boom structure as shown later.

Ship-induced loads

Little information was found in the literature on ship-induced loads in ice booms. Uzuner (1975) reports that, for the Copeland Cut test boom, the loads were relatively small compared with steady-state loads. The force level seems to depend upon how well a passing ship mobilizes the ice cover.

Only a few factors are known: 1) Generally, a fragmented ice cover starts to move over the ice boom when wave action takes place at the boom. 2) A solid ice cover is much stiffer or more resistant to deformation than the ice boom structure and is usually frozen to shore; subsequently, a direct thrust on the cover may not register on a force sensor in the structure. 3) If the solid ice cover is depressed or generally lowered from ship propulsion effects, or from river flow reduction, and the shoreline acts as a hinge point, the force registered on the force sensor can decrease. The reason for this decrease is that the anchor rope rotates or swings down about a different point from that of the ice and becomes foreshortened. 4) Finally, it is well known that ships can break ice directly by contacting it, and indirectly by causing wave action.

Based on the above information, the following actions might be expected to result from ships passing through the ice booms: 1) Some ice would be broken, but probably into pieces composing not more than a small fraction of the design areas. 2) Some ice would be washed over the ice boom. 3) An ice sheet would rise up sufficiently at the boom in response to a ship's bow wave and increase the load registered in the structure. 4) The ice sheet would be depressed sufficiently at the boom by ship propulsion effects and decrease the load registered in the structure.

Ice Barrier Reaction Force

The ice boom construction contractor was given a choice between using a steel pontoon boom and a

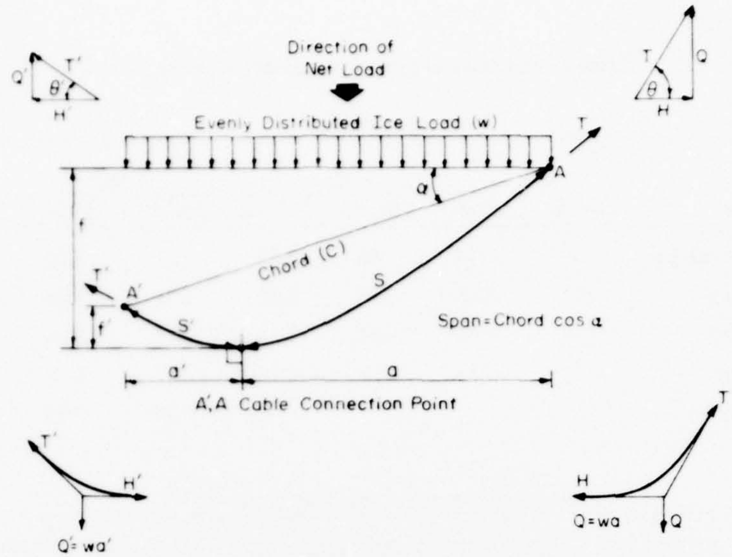


Figure 6. Parabolic cable loads and cable length definition.

timber boom. He chose the timber model, whose design was taken directly from the design of the Copeland Cut test boom with no modifications. The original estimate of the ice retention capability of the timbers was 130 lbf/ft (1897 N/m). This capability, however, applied only to the unconsolidated ice cover phase. Later, when the ice cover becomes solid, it is often frozen to the timbers. When this happens, the ice boom can restrain the ice cover with its maximum structural capacity.

ICE FORCES IN THE STRUCTURE

Analytical Relationships

The line of action of the ice cover may be perpendicular to the chord of one particular section and at the same time it may be at an oblique angle to the next section. The analysis of forces had to be general enough to account for the effect of this obliqueness.

The ice forces were assumed to be evenly distributed along a line perpendicular to the line of action of the ice area. The ice boom would therefore have the shape of a parabola with its axis parallel to this same line of action. The validity of the latter assumption has been indicated by studies of ice booms on the St. Lawrence River, especially on the Beauharnois Canal (Perham and Racicot 1975), except that the cable-to-chord-length ratios of 1.044:1 and 1.25:1 found in these studies were different from the present ratio of 1.3:1.

Equations for evaluating the forces once the geometry of the ice boom has been established may be found in many textbooks, such as that of Timoshenko and Young (1956). Diagrams of the interaction between the distributed load w acting over part of the cable span a or a', the force at the low point of the cable H, and the force at the ends of the cable T or T' are shown in Figure 6.

The equation for the length S of the parabola from the tangent at the low point of the cable to the end of the cable, as diagrammed in Figure 6, is

$$S = f\left\{\sqrt{1 + a^2/4f^2} + \frac{a^2}{4f^2}\left[\ln\left(a + a\sqrt{1 + \frac{a^2}{4f^2}}\right) - \ln\left(\frac{a^2}{2f}\right)\right]\right\} \qquad (5)$$

S' may be similarly found.

The forces T and T' are calculated by the usual method of statics. But eq 5 is used to find a practical balance between the length of the cable $S + S'$ and the transverse cable force component H which increases as the cable-to-chord-length ratio approaches unity.

Design Force Summary

The rather flexible method of analyzing the boom structure forces that was employed here was used because it was obvious that the forces could come from

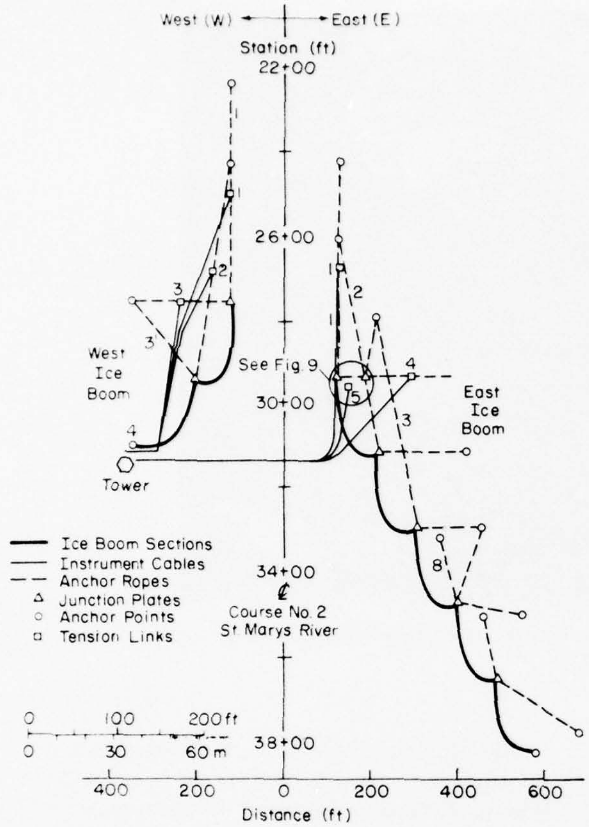


Figure 7. Plan view of ice booms showing anchor ropes and instrument locations.

a range of directions to act on any one line of booms. The structures, especially the west boom, could have been made a little more efficient by changing one or two anchor locations, but time constraints did not permit this. However, some advancements in ice boom technology seemed to be needed for these navigation booms to be successful and this was taken care of first. These special features are described in the next section.

The design force estimates are summarized in Table II for the fully intact booms, as shown in Figure 7, and are based on the maximum loading from Table I. Figure 7 is a scale drawing of the ice booms showing their component lengths and locations to scale as they were installed and used in the locations shown in Figure 3.

Table II gives the majority of the design data used by the Detroit District, U.S. Army Corps of Engineers. Some additional information was provided that resulted from what may be referred to as a failure analysis of the west ice boom. The effects of the loss of the small anchor cables, the C3W′ and the C3W cables,

Table II. Estimated design forces of St. Marys River ice booms.

Structure part no.	*Force (lbf)*	*Force (kN)*	*Structure part no.*	*Force (lbf)*	*Force (kN)*
B1W	68,000	302	C1E	43,000	191
B2W	73,000	325	C2E	45,000	200
A4W	73,000	325	C3E	38,000	169
C1W	65,000	289	C4E	5,000	22
C2W	52,000	231	C5E	8,200	36
C3W	11,000	49	P1E	7,000	31
C3W′*	48,000	214	C(J2-A3)E	500	2
B1E	43,000	191	C6E	14,000	62
B2E	45,000	200	C7E	11,000	49
B3E	38,000	169	C8E	22,000	98
B4E	32,000	142	C(J5-A7)E	24,000	107
B5E	27,000	120	C9E	20,000	89
			C10E	26,000	116
			C11E	10,000	44
			A12E	15,000	67

* See Table A1; "C3W′ broken" for force estimate prior to adding this cable, which was not originally considered. A = anchor point, B = boom section, C = anchor rope, P = pipe restraint.

were calculated; these are given in Table A1, App. A. This analysis also resulted in the incorporation of cable C3W′ in the west ice boom.

The components identified in Figure 7 by numbers were associated with force measurements except for anchor cables number 2, 3, and 8. These cables are discussed later as diagonal anchor cables. The curvatures of the floating ice boom sections based upon mathematical computations compare well with those of aerial photographs of the installation as shown in Figure 8. The boom structures are composed of 3 shore anchors, 13 river bottom anchors, 17 anchor cables and 7 boom cables. The boom cables are 250 ft long (76.2 m) and the length-to-chord ratio is approximately 1.3:1. There is at least one flotation buoy at each junction plate. Each timber is 1 ft × 2 ft × 20 ft long (0.30 × 0.61 × 6.10 m long).

SPECIAL FEATURES

Extension of West Ice Boom

Initially, the west ice boom had one section perpendicular to course 2 (Fig. 5). The opening between the

Figure 8. Aerial view of installed ice booms, looking downstream along course 2, St. Marys River, Michigan, 23 December 1975.

two booms was 250 ft long. A review of aerial photos and some speculative thinking indicated that it might be possible for a large ice sheet to break off from the southwest portion of Soo Harbor and move unimpeded across the opening to strike the upstream end of the east ice boom. The resulting load could be substantial; therefore, it was decided to extend the west boom upstream one more section to increase protection of the east boom provided the main function of the ice boom set was not adversely affected by the change. Renewed model tests indicated that the harbor ice loss increased, but because the increase was not substantial, this change was accepted.

Pipe Restraint Structure

The structural arrangement shown in Figure 9 was devised to hold the upstream end of the east ice boom at the edge of the navigation channel against an opposing force without having guy wires or anchor cables extend out into the channel. The channel has no extra depth to safely allow cables beneath a large ship. Any cables, therefore, that protrude a certain distance into the opening reduce by the same distance the space available for ships to pass through without reducing similarly the space available for passing ice.

The main source of loads on the upstream end of the east boom is water flowing parallel to course 2 (Fig. 5). The load at this end of the boom has a component which is directed away from the boom opening. The lateral load can be reduced by making the boom rope longer, but getting the force near zero requires an excessive length. Also, under some wind conditions, a very long cable could be bowed out with ice and thus block most of the opening. It would be very troublesome if the ice were frozen in this shape.

The pipe restraint structure is composed of a horizontal column supported by two large buoys and held in place by three heavy cables and one light one. The ice boom section and the main anchor rope are connected to the channel end of the pipe. The two lateral-force carrying anchor cables are attached to the opposite end of the pipe. Restraint is needed in both directions because of the wind forces. A third anchor rope is attached to the latter end to hold it in position against the hydrodynamic drag of the water flowing at approximately 2.7 ft/s (0.82 m/s) past the 16-in. (0.41-m)-diam ×60-ft (18.3-m)-long pipe. Figure 10 shows the pipe with buoys attached being lowered into the water.

Other methods, such as use of a spud barge and a diagonal column, were considered for this location but were eliminated mainly because of safety factors

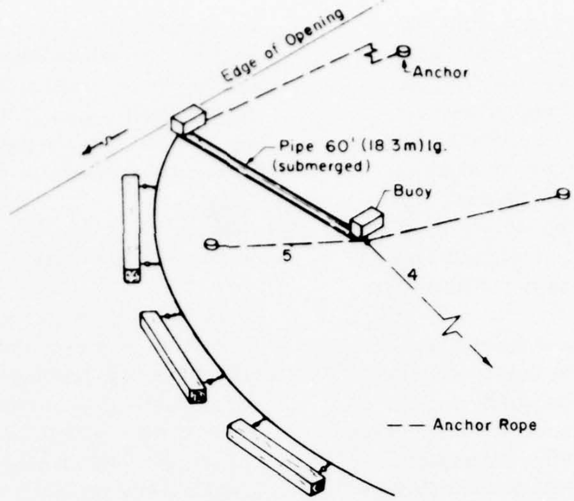


Figure 9. Pipe-restraint structure of east ice boom.

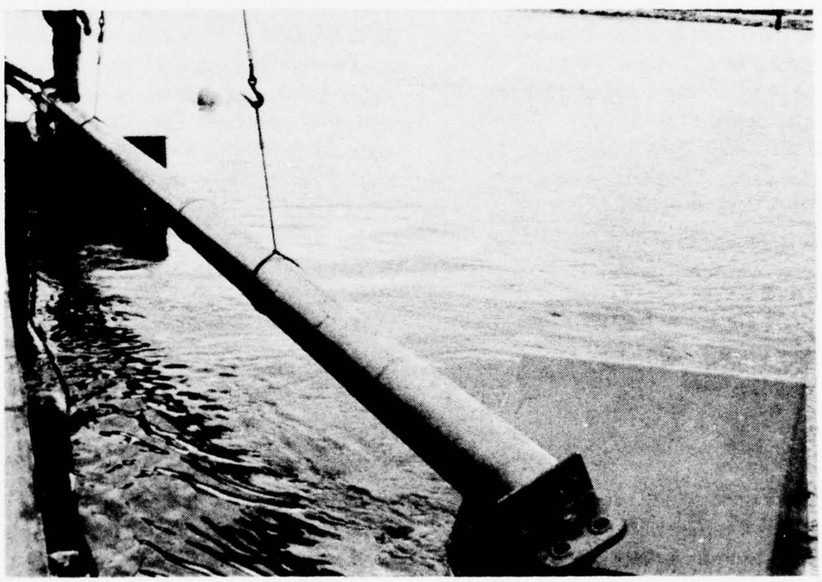


Figure 10. Restraint pipe and floats being installed.

relative to shipping. At least, the pipe restraint behaves like other parts of the ice boom and permits excessive loads to pass over it.

Diagonal Anchor Cables

One other characteristic of these ice booms, especially the east boom, is the main anchor cables at small angles to the main directions of force. Examples are cables C2E, C3E, and C8E (Table II). This method increases the load to each of the connected anchor ropes, by approximately 5%. The main function of this arrangement is to provide reaction against the force of winds coming from a southerly direction that could blow the ice booms back away from the channel.

Measurement Systems

Six force measurement systems were built into the anchor rope structure at the upstream ends of the east

and west ice booms; three systems were built into each boom. Each system consisted of a protected load sensor, or tension link; an armored electrical cable; a power supply; and a recorder. These systems are basically the same as the one described by Perham (1974), but contain a few minor modifications. A simplified electrical circuit diagram of the system is shown in Figure A2, App. A. The sensitivity of each load sensor is given in Table AII, and a photo of a partly assembled sensor is shown in Figure A3, App. A.

Each load sensor was installed at the midpoint of its anchor cable where it would be deep under water and away from ice action. Its signal cable was run along the river bottom to shore where it emerged from the river bank through a 6-in. (0.15-m)-diam steel conduit. Each signal cable was held down by anchors spaced every 100 ft (30 m), or every 50 ft (15 m) where the cables crossed the navigation channel. Each cable was also secured to a shore anchor point. The shore end of each cable was connected to its power supply and recorder in a cabinet located in a small heated trailer near the shore anchor point of the west ice boom (Fig. 3, center right).

The systems were checked by Soo Area Office personnel at least twice daily. The charts were sent to CRREL weekly. A force data sheet was kept daily to show key periods when the recorder charts should be carefully inspected.

MEASURED ANCHOR CABLE FORCES

Data Records

A substantial quantity of force and supplemental information was obtained this past winter, the most significant of which is given in this report. Periods of inactivity (no force changes) took up much of the time. There were also many times when there was activity but the force levels, such as those caused by ship passages, which cause only a slight blip on the signal trace, were almost negligible. Nevertheless, this information is quite valuable.

Much of the representative force data were given on the daily log sheets. This information was backed up by the force recorder charts which were reviewed for more information. Six signal traces have been copied from these charts and are shown later (4 in Fig. 11 and 2 in Fig. A4, App. A).

The supplemental data consisted of weather data, water level information, ship traffic information, and notes written by the observers on the data sheets, on the recorder charts, and in the log book. The weather data were supplied by the U.S. Coast Guard and by the National Weather Service (National Oceanic and Atmospheric Administration), Ashville, North Carolina. The ship traffic records and water levels were provided by the Soo lock personnel.

Average and Peak Loads

The plan view of the booms shown in Figure 7 gives the locations of the six load sensors (tension links). Table III summarizes the peak loads that were expected in these cables and compares them with the measured values for the winter of 1975-76.

The west ice boom was fully intact during periods 1, 2, and 5. During period 3, the C3W′ cable was broken. Although the C3W′ cable was not instrumented, this condition was obvious from photographs showing the shape of the boom during this period. During period 4, both the C3W and the C3W′ cables were broken.

The average loads registered in the ice booms never exceeded or were near the predicted loads. Some of the peak loads, however, exceeded the design values under rigorous conditions which developed when no observers were present. These were those given for the C1W, C2W, and C1E cables, which occurred the morning of 1 Feb 1976. The forces and times for this period and some preceding and following periods are given in Table AIII, App. A.

Ice Activity on or about 1 February 1976

Force activity started the evening before 1 February. At that time, some relatively high forces were registered, especially at C1W and C3W, shown on Table AIII. The ice cover seemed to stabilize again until the time of the previously mentioned peak forces. At this time the ice cover behind the west ice boom was thought to have been nearly complete and it started to move over the ice boom. The float at the upstream end of the west boom could not submerge and was broken off by a measured force of 88,000 lbf (391 kN) on 1 Feb 76 at 0636 hours. The float is like those shown in Figure 9 at the ends of the pipe.

The C3W′ cable was apparently overloaded at this time, probably by ice action on the two floats at the boom end of the cable. The ice sheet is believed to have slid across the boom opening and impinged on the ice at the upstream end of the east boom, breaking some of the ice and moving against the C1E anchor rope to cause high forces there. The resultant loading on this cable was not characteristic of a dynamic load in the

Table III. Peak loads and average loads in selected periods, 1976.

Anchor cable	Expected load (lbf)	Expected load (kN)	Force recorder charts (lbf)	Force recorder charts (kN)	Weekly data sheets (lbf)	Weekly data sheets (kN)	Tension link design capacity (lbf)	Tension link design capacity (kN)
	Peak loads							
C1W	65,000	289	77,000	343	70,000	311	180,000	801
C2W	97,000*	431	94,000	418	75,000	334	180,000	801
C3W	13,000	58	53,000	236	50,000	222	60,000	267
C1E	43,000	191	160,000†	712	9,900	44	120,000	534
C4E	5,000	67	4,100	18	500	2.2	60,000	267
C5E	8,200	36	1,500	7	200	0.9	60,000	267

Average loads during selected periods

Anchor cable	1 14 Jan 76 (lbf)	(kN)	2 24-31 Jan (lbf)	(kN)	3 15-22 Feb (lbf)	(kN)	4 23-27 Feb (lbf)	(kN)	5 29 Feb-7 Mar (lbf)	(kN)
C1W	4,590	20.4	6,800	30.2	13,200	58.7	19,400	86.3	9,290	41.3
C2W	1,640	7.3	480	2.1	8,550	38.0	9,740	43.3	960	4.3
C3W	1,600	7.1	4,130	18.4	8,280	36.8	100*	0.4	3,430	15.3
C1E	6,080	27.0	6,000	26.7	0**		0		0	
C4E††	0	0	0	0	0		0		0	
C5E††	0	0	0	0	0		0		0	

* Cable C3W was broken during this period.
† Was 10,500 lb (46.7 kN) before the impact of a moving ice sheet caused this load.
** Became inoperative 1 February 76.
†† The east ice cover solidified before these dates.

cable structure alone and must have been due therefore to the coupled interaction between the cable and a large ice sheet.

The Soo locks ship log does not indicate any ship activity at these times, so the ice activity was considered due to natural causes. A related event was a 4-in. (0.1-m) rise in water level on 31 January which may have helped break the ice free from shore. The wind data for that time are somewhat contradictory and it is not clear whether the wind helped to initiate the ice action or to stop it on that date. Ice action was continued the next morning under the influence of a strong northwesterly wind.

C3W Cable Forces

The peak forces in the C3W cable exceeded the expected values several times during the winter because of the presence of large moving ice sheets. The design force values, based upon the fragmented ice cover theory, gave a value of only 13,000 lbf for the load in this cable. Also, the cable load for an ice restraining capability of 130 lbf/ft (19 kN/m) was much smaller than this, even with the C3W' cable broken. It appeared therefore that the two conjoined cables, C1W and C3W, were being loaded mainly through the flotation buoys when peak forces occurred.

To check out this supposition, an analysis was made of ice acting under certain constraints on the junction point. The ice cover was assumed to be a solid sheet and sliding along the southerly shore of Soo Harbor just upstream of Mission Point without rotation. While under this condition it was assumed to be restrained by the float acting independently of the timbers. The cables were assumed to respond and to achieve the force balance required to stop the ice without dynamic effects.

The deformation characteristics of the anchor cables were determined from their lengths and physical properties. Each was made from 100 ft of chain and a specific length of wire rope of compatible strength;

the different elongation characteristics of the chain and wire rope were considered. Table IV gives an estimate of the force/deformation ratio for several of the lines.

Table IV. Estimate of force/deformation ratio for some anchor cables.

Anchor cable	With chain section (lbf/in.)	(kN/m)	Without chain section (lbf/in.)	(kN/m)
C1W	1,236	2.16		
C3W	808	1.42	3,116	5.46
C3W'	802	1.40	2,984	5.23
C1E	984	1.72		

Under the above assumptions, the force in the C3W anchor cable could be about one-half the value of that in the C1W anchor line or much higher than expected from unconsolidated ice cover considerations. There were circumstances, however, when the measured force on C3W was as great as that on C1W. This was probably due to either the rotation of the upstream end of the ice sheet out toward the ship track or the wedging action of small ice jams that occurred at Mission Point, or both.

These factors are emphasized here because they relate to, or are due to, the uniqueness of this application. If the booms and opening were used perpendicular to a long straight river or channel, the loading considerations would no doubt be much simpler. But this method, which is generally associated with statically indeterminate problems, may have further application in ice booms in the future.

Ship-Induced Loads

There are myriad ways in which ships may interact with an ice boom; these include load transfer from shore to boom, icebreaking, indirect contact through moveable ice, water level and flow momentum changes, flow area changes, wave action, and damping effects. A variety of supplemental information is required to evaluate the effects of some of these, and the Soo Harbor and ice boom location are not ideal areas even for simple analyses, much less detailed hydrodynamic calculations.

It was felt, therefore, that the most important aspect of the data obtained thus far is the peak loads that occur in the boom structure as a consequence of the passage of ships.

The time ships pass through the ice booms is also considered important. It was thought initially that the Soo lock's log book would give the time of passage closely enough merely by adding or subtracting the normal travel time between the booms and the locks. However, this method did not work out well because of the waiting periods that the ships often incurred during the winter. Also, it was difficult to tell from the recorder trace whether a load fluctuation was induced by ship passage or happened naturally.

Fortunately, the Soo Area Office observers, as requested, put event marks on the force recorder traces when many of the ships went through. Of these periods 38 were evaluated for peak forces; 6 of them involved the passage of 2 ships almost simultaneously. The passage of ships was noted 36 other times, but the changes in forces at these times were indistinguishable or negligible. Approximately two-thirds of the latter events were passages by Coast Guard vessels.

Only the C1W cable was evaluated for peak forces. The tension links in the C3W and the C2W cables also showed similar responses to the passage of ships, and, although minor differences in force variation patterns of the three systems were observed, they were not analyzed in detail.

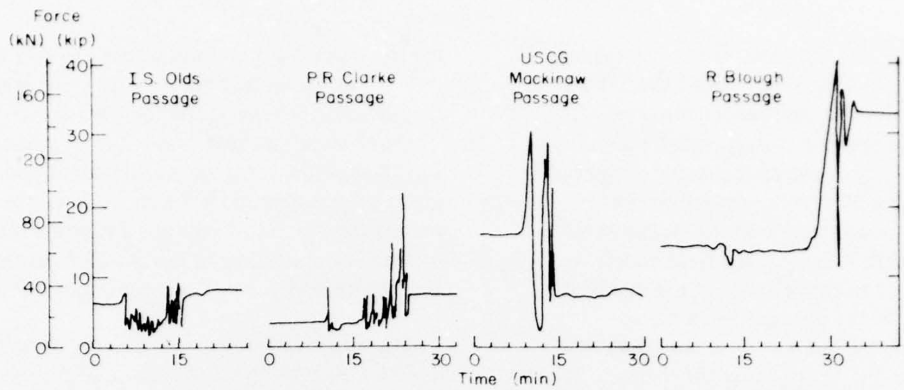
The evaluation consisted of copying each trace section, and calculating the force level at several points on the section. Four representative traces are shown in the summary of results given in Figure 11.

The passage of ships affected the ice cover for only a relatively short time. The average duration of the force fluctuations that were investigated was about 15 minutes. After this activity ended, it was found that the net effect that it had had on the loads registered in the anchor rope was that the loads were generally higher or lower than before the passage of the ships; i.e., loads were either transferred to the boom from shore or vice versa.

Figure 11 and Table V give representative results. It should be noted, however, that the signal traces are characterized more by their individual differences than by their similarities. Also, the traces that are shown are not necessarily representative of the named vessel but were shown to indicate a certain force level.

The peak force levels were higher for some ships than for others; therefore, these levels were averaged for 14 ships regardless of whether there was one data point or several points for each ship. It was found that these averages were generally in the four categories shown in Table V.

The force variation patterns resulting from ship passages were similar to those resulting from natural effects; but they appeared to be affected by the size of the ship and the way in which it was operated or



Force level (kips)	Force level (kN)	Ships	Direction	Date	Time (hr)	Peak force (kips)	Peak force (kN)
10	44	*I.S. Olds*	downbound	14 Jan 76	1010	9.9	44
20	89	*P.R. Clarke*	upbound	20 Jan 76	2100	21.9	97
30	133	USCG *Mackinaw*	downbound	5 Mar 76	0932	30.8	137
40	178	*R. Blough*	upbound	22 Feb 76	2006	40.4	178

Figure 11. Representative load fluctuations.

Table V. Peak forces summary

Category	*C1W Anchor cable peak force level (kips)*	*(kN)*
Average for upbound vessel passages	24.1	107
Average for downbound vessel passages	25.9	115
Average for all vessel passages	25.0	111

Distribution:

Average peak force level (kips)	*(kN)*	*No. of ships causing these force levels*
40,000	173	1
30,000	133	3
20,000	89	3
10,000	44	7

perhaps by the power level that was applied. The highest forces measured in the ice boom structure were registered when both of the small cables C3W and C3W′ were broken. The boom loads appeared to be exaggerated then because the load formerly carried by these two cables was transferred to the other cables, especially the instrumented ones. The peak ship-induced force was 63 kips (282 kN), on 25 February 1976. The

peak ship-induced force that occurred when the ice boom structure was fully intact was 47 kips (209 kN), on 22 Mar 1976 (the boom had been repaired).

Table V shows that the average peak force for upbound ships is nearly the same as that for downbound ships. Further, the difference between the two averages is but a small fraction of the measured force level. This seems to mean that the force activity is mainly in response to the presence of the ship in the channel and not to the direction of its travel.

The reason for this result may be the effect that the ships have on the waterflow in the channel. The presence of these ships, especially in the ice-covered channel, would partially block the flow because the submerged area of many of the ships is equal to 10% or more of the channel flow area and their lengths are often greater than the channel width.

Not enough information was obtained, however, to evaluate this phenomenon, but a related type of physical occurrence has been studied for many years. Tests have shown that ships that travel from deep water into channels of restricted depths experience an increase in resistance to their movement (Todd 1967).

The potential flow around a ship is changed, especially along its bottom. Here the waterflow must speed up because of the restricted space and, consequently, the pressure on the bottom is reduced and the pressure distribution there is changed. The net effect of these changes on the ship is to increase its frictional resistance and sinkage, or draft, and to change its trim, or fore and aft attitude. Each of these contributes to its total resistance. In addition, when the ship is moving in a channel that also has a restrictive width, such as the Little Rapids Cut, these changes are further aggravated.

The passage of ships through the ice cover behind the booms affects the physical conditions under the cover in a similarly complex manner. The water level there would tend to increase and provide more flow area to compensate for the reduction in flow area caused by the ship, but conversely any flow velocity increases would probably modify this tendency. The quantity and timing of water level changes are not now known, except that they seem to activate the cover sufficiently to let at least part of the ever-present drag forces on it be applied to the boom.

Ice Cover Load Check

From 17 to 22 March, the ice cover behind the west ice boom was at times free from the shore, and at times the ship track was free from the ice. During this period, only the ice boom held back the ice cover against the drag of water beneath it and the wind above it.

On 18 March, at 1610 hours, the ice cover moved slightly, but did not move over the boom and consequently a combination of forces developed in the load sensors (tension links). Almost the same combination occurred on the following day, at 2005 hours, just before the ice cover moved over the boom and took float with it.

The measured force on the cover at these times was 36 kips (159 kN), and because of the mild wind conditions, this force was due mainly to the water drag beneath it. By comparison, the water drag force was estimated originally to be 126 kips (560 kN), but this force was based on a design river flow of 85,000 ft^3/s (2,435 m^3/s) and a roughness constant of 25 (see eq 3). The flow in the river on 18 and 19 March was about 70,000 ft^3/s (1,982 m^3/s).

Pariset and Hausser (1961) also give the roughness constant a value of 25 to 30 $ft^{1/3}/s$ when the ice cover first forms, but say that it changes gradually to 35 to 45 $ft^{1/3}/s$ as winter continues because of the general smoothing effect of water flowing beneath the cover. These latter values seem to apply, although the ice cover during their study was not completely stationary.

An estimate of the loads to be expected from the ice cover under the above changes can be obtained by multiplying the original load estimate by the square of the ratios of the original and the new values as shown below

$$F_n = F_0\left(\frac{Q_n}{Q_0}\right)^2 \left(\frac{K_0}{K_n}\right)^2 \qquad (6)$$

where F_0 = original load estimate
Q_n = new flow quantity
Q_0 = original flow quantity
K_0 = original roughness constant
K_n = new roughness constant.

For Q_n = 70,000 ft^3/s and K_n = 35, F_n = 42.6 kips (190 kN), while for Q_n = 70,000 ft^3/s and K_n = 45, F_n = 25.8 kips (115 kN). The measured value of 36 kips (159 kN) is nearly an average of these estimated loads.

The effect of movement in an ice sheet was indicated somewhat by the forces that were registered 5 or 6 minutes later while the ice was moving over the boom. At that time, maximum resultant force of 70 kips (310 kN) was measured by the gages.

The effect of wind on the ice cover was indicated on 21 March at about 1340 hours. The Coast Guard wind

data indicated strong, 21-mph (33.8 km/h), west and northwest winds, and this condition was noted twice in the log book for that day.

High forces occurred, again when some ice was moving over the boom. The force of 92 kips (410 kN) achieved then seemed to be influenced by the wind because it was higher than the previously mentioned water drag and ice momentum effects of 70 kips (310 kN). The expected drag from the above wind would be about 15 kips (67 kN). This value, when added to the previous 70 kips (310 kN), would come within about 8% of the above figure. Perhaps with closer scrutiny of the ice cover areas and better wind measurements, i.e., at the site, it would be possible to better evaluate the wind drag coefficient using the ice boom forces system at some later date.

CONCLUSIONS

1. The ice booms were generally successful in stabilizing the ice cover and in restraining it sufficiently to make manageable other ice control efforts relative to ship navigation in Soo Harbor and in Little Rapids Cut.

2. Instrumenting the ice booms for restraining ice forces was a good investment for several reasons:

a. The data indicated periods when the ice acted as predicted on the ice booms.

b. The data indicated other periods when the ice acted differently than planned for on the ice booms.

c. The data indicated the effect of ship passages on the interaction of the ice cover and ice booms.

d. The data helped to evaluate the occurrence of certain important incidents such as line breaks in the booms.

3. The west ice boom was heavily loaded several times during the winter for a variety of reasons, the main one being that the ice cover never became frozen to shore. The data indicate that, while initially thought to be made possible by the thermal effluents on the south shore, the passage of ships, especially large ships, through the ice cover upstream of the Little Rapids Cut, could contribute strongly to breaking the ice free from shore.

4. The ice boom timbers used in this study exhibited an ice barrier capability of about 50 lbf/ft during the unconsolidated-ice-cover phase of cover formation.

5. After the ice cover became an essentially solid ice sheet, the heaviest loads on the west ice boom structure came from ice acting on the junction floats.

6. The effect of passing ships was mainly to break the loaded ice cover free from shore and let it act on the ice boom, although the way in which the ship was operated could affect the level of force on the ice achieved. The causes were probably increases in the average water level and the local flow velocity at the times of increase.

7. The east ice boom became full of ice under the influence of the waterflow and a northerly wind. The ice cover solidified while under these influences, and it restrained or protected the ice boom structure from any further loading, except once when the cover was broken by the impact of a large moving ice sheet.

8. The movement in an ice sheet seemed to cause it to act with greater force upon the ice boom structure.

9. The floating ice barrier remained intact on the surface throughout the winter in spite of the separation of two small anchor ropes from the booms and unexpectedly high loads due to the interaction of the solid ice cover and float.

10. The pipe restraint structure performed flawlessly in supporting the upstream end of the east ice boom.

RECOMMENDATIONS

1. The ice booms can be reinstalled without change another year provided the ice forces that were measured this year are acceptable for the anchors and anchor ropes to which they were applied.

2. The east ice boom should be reinstalled as it is, except that the two-float arrangement should be modified because the floats are too close together and can collide under wave action. Perhaps one float would be sufficient.

3. The timbers used on the ice booms tilt or pitch forward an excessive amount; i.e., the upstream corners of the tops of the timbers are 6 or 8 in. under water in places. This condition lets the ice slide over at a lower than necessary force level. The upstream corners should be at water level, or nearly so, to be most effective in holding back the rather thin ice present early in the winter. Perhaps additional timbers and floats could correct this condition.

4. The ice pressure or distributed load that the timbers can withstand should probably be increased. Although some of the forces applied to the ice boom structures this past winter were nearly twice the expected values, they were due mainly to the solid ice acting as a concentrated load on the floats and not as a distributed load in through the timbers. Even if the present timbers could hold back the predicted 130

lbf/ft (19 N/m), the approximately 400-ft-long (122-m) west ice boom would restrain only one-quarter of the force that could be generated in the ice cover. It is hoped that the shoreline will provide the additional restraint needed. However, if this does not happen, the ice boom will sink and let the ice pass over it when the force becomes too great.

5. Several changes should be made in the west ice boom to make it restrain the ice cover more effectively.

a. For some reason or reasons, the timbers are submerged and tilted more in this ice boom than in the previous Copeland Cut test boom. This condition reduces the ice-restraining capability of the timbers. This ice boom seems to need more distributed flotation. Perhaps a few timbers could be removed from the east ice boom and added to the west ice boom.

b. The structure of the west ice boom should be extended upstream one or two more lengths to help it hold the ice cover stationary. The load from the southwest harbor ice cover would then be distributed over several more timbers, floats and anchor ropes.

c. The C3W' anchor cable received rather heavy loads this past winter and thus would be a good one to have instrumented to measure forces. As part of the measurement program, though, it would be better to have the cable going to its own anchor point at right angles to course 2. With this orientation it would probably be easier to distinguish between ship effects and natural responses.

6. Should it be decided to reinstall the ice booms, it would be a good idea to reinstall some or all of the force measurement systems. It is suggested that four systems be used on the west ice boom, the three used last winter and the one mentioned in 5c. The most force data could be expected from this boom without the ship channel's being crossed with instrumentation cables.

7. A few changes in, or additions to, the methods, procedures, and types of supplemental data gathered should be made:

a. A wind velocity and direction recorder should be installed at or near the ice boom site.

b. A wave-height recorder should be added to the site to evaluate the effect the ships have on the water level at the site.

c. The speed of the ships should be measured as they pass through the ice boom opening and recorded along with the times of passage and the ships' names.

d. The Soo Area Office observers devised a worthwhile addition to the study program part way through the winter; this was a sketch or diagram of part of the river in the vicinity of the ice boom, on which was drawn the extent of the ice cover and its cracks, holes, overhangs, etc. Another diagram could be made which shows most of the Soo Harbor and Little Rapids Cut areas. When a lot of ice is moving, quick sketches could be drawn on a copy of the diagram to show the area of ice lost by the harbor and gained by the cut during certain periods of time.

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APPENDIX A. ST. MARYS RIVER ICE BOOMS TEST DATA

Chronology of operation

Date	*Event*
21 Dec 75	Installation of the tension links and signal cables in river was completed.
1 Feb 76	Something broke on the west ice boom. (It was eventually determined that the float connection and the C3W′ anchor rope broke.)
2 Feb 76	The loss of the large buoy on the upstream end of the west ice boom was confirmed.
3 Feb 76	TIE tension link system was damaged somehow. Ship traffic affected the ice cover. The ferry track filled up but was cleared by night.
13 Feb 76	The flotation buoy was reinstalled on the west ice boom upstream junction plate on or about 1400 hours.
22 Feb 76	C3W anchor rope broke in the 1.0-in. chain section 40 ft from the anchor point. The force was 42,000 lb (187 kN).
22-27 Feb 76	Substantial force registrations were noted in the west ice boom during the whole week.
28 Feb 76	The Soo Area Office repaired C3W and C3W′ anchor ropes; it also relocated the T3W tension link to the junction plate position.
18 Mar 76	Substantial force levels were once again registered on the west ice boom; southwest harbor ice sheet was free from shore.
19-22 Mar 76	Shipping track was open all the way to the locks. The southwest harbor ice sheet was broken from shore. Warm spell occurred. The forces were checked at this point.
20 Mar 76	Float at center of west ice boom broke loose and was retrieved by the USCGC *Arundel*. Cable clamp had broken. Temperatures were in the mid forties (°F) (~ 7°C).
21 Mar 76	Force on T3W at 1336 hours was 53,000 lbf (236 kN), the highest for the year on that particular anchor rope. Temperatures cooled off again.
22 Mar 76	At 1520 hours, the float at the upstream end of west ice boom broke loose again. It was retrieved by USCGC *Naugatuck*.
24 Mar 76	At 1200 hours, the above float was reinstalled.
25 Mar 76	Soo Harbor was basically free of ice.
29 Mar 76	Only broken ice remained behind the west ice boom; 75% of the cover behind the east ice boom remained.
7 Apr 76	Ship traffic started to increase appreciably.
14 Apr 76	Heavy ship traffic was noted.
16 Apr 76	Some ice still remained behind both ice booms.
19 Apr 76	The Soo Area Office began removal of west ice boom.

Table AI. Forces in the west ice boom under three additional conditions.

Cable or anchor	Distribution load of 130 lbf/ft (19 N/m) (lbf)	(kN)	Original loading, but with C3W and C3W′ broken (lbf)	(kN)	C3W′ broken (lbf)	(kN)
B1W	15,800	70.3	73,000	325	57,000	254
B2W	20,000	89	120,000	534	94,000†	418
A4W	16,700	74.3	120,000	534	105,000	467
C1W*	15,300	68.1	73,000	325	56,000	249
C2W*	10,000	44.5	82,000	365	97,000	431
C3W*	3,800	16.9			13,000	58
C3W′	16,000	71.2				

* Instrumented cables.

† Force at end opposite anchor A4W.

Table AII. Physical and electrical factors, St. Marys River ice boom forces measurement systems.

Tension link (sensor)	Rated load (lbf)	(kN)	Output* (mV)	Channel	Recorder† resistor R_s (ohms)	Calibration signal (mV)
T1W	180,000	800.7	74.8	A1	59,880	17.5
T2W	180,000	800.7	75.2	B1	57,983	18.1
T3W	60,000	266.9	58.1	A2	57,983	18.1
T1E	120,000	533.8	73.0	C1	46,400	22.5
T4E	60,000	266.9	52.1	B2	46,400	22.5
T5E	60,000	266.9	58.8	C2	46,400	22.5

* 12 Vdc input voltage.

† Recorder settings: voltage range: 100 mV full scale (10 in. or 0.25 m on chart); chart speed: 2 in./hr (14.1 μm/s). R_s is shown on Fig. A2.

Table AIII. Major force fluctuations, St. Marys River ice booms, 31 January-3 February 1976.

Date and force levels	*Time (hr)*	*Forces on respective tension links**							
		T1W		*T3W*		*T2W*		*T1E*	
		(kips)	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*	*(kips)*	*(kN)*
31 Jan 76									
Initial	1930	6.2	27.6	5.7	25.3	0	0	10.5	46.7
Peak	1945	33.0	147	35.3	157	0	0	10.5	46.7
Final	2130	19.0	84.5	24.0	107	0	0	10.5	46.7
1 Feb 76									
Initial	0632	27.0	120	23.3	104	0	0	10.5	46.7
Peak	0636	77.0	343	42.0	187	94.0	418	10.5	46.7
Final	0650	1.2	5.3	0.4	1.8	2.5	11.1	10.5	46.7
Initial	0651	1.2	5.3	0.4	1.8	2.5	11.1	0	0
Peak†	0651+18 s	1.2	5.3	0.4	1.8	2.5	11.1	8.8	8.7
Return		1.2	5.3	0.4	1.8	2.5	11.1	0	0
Peak	0651+50 s	1.2	5.3	0.4	1.8	2.5	11.1	108	480
Return								0	0
Peak	0652+12 s	1.2	5.3	0.4	1.8	2.5	11.1	160	712
Return								0	0
Final	1130	2.5	11.1	1.0	4.4	10.0	44.5	0	0
2 Feb 76									
Initial	1822	2.5	11.1	1.0	4.4	10.0	44.5	0	0
Peak	1825	45.0	200	6.8	30.2	75	334	0	0
Final	1835	1.2	5.3	0.4	1.8	6.0	26.7	0	0
3 Feb 76									
Initial	1900	1.2	5.3	0.3	1.3	10.0	44.5	0	0
Peak	1909	9.5	42.3	1.3	5.8	20.0	89.0	0	0
Final	1923	1.2	5.3	0.2	0.9	2.0	8.9	0	0

* The forces in tension links T4E and T5E remained essentially zero and thus are not included here.

† Series of three peak loads of very short duration.

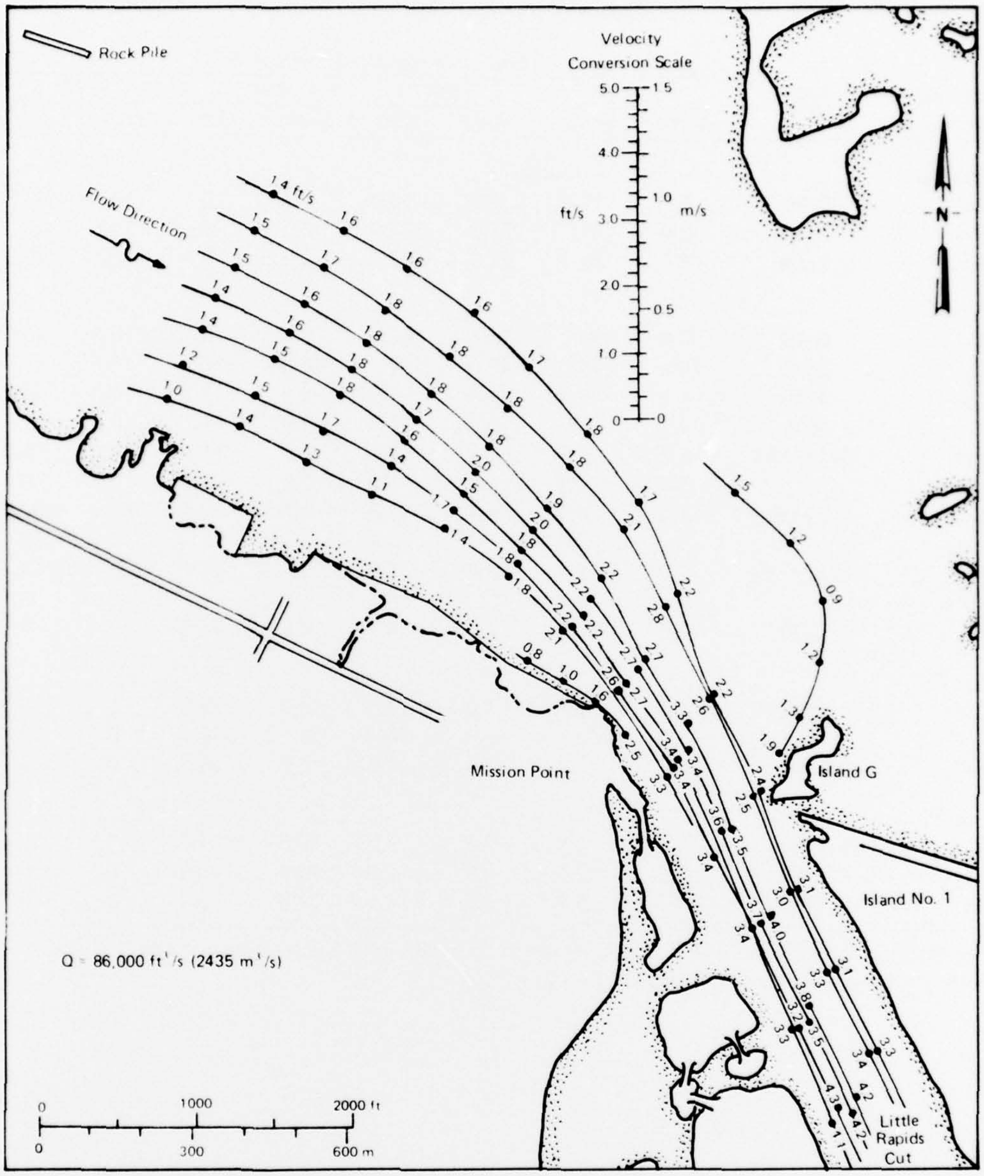

Figure A1. Representative water velocities and streamlines leading into the Little Rapids Cut section of St. Marys River. (Acres American Inc. 1975.)

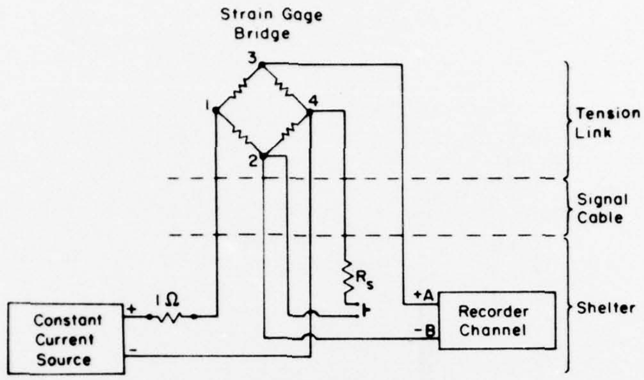

Figure A2. Force measurement circuit.

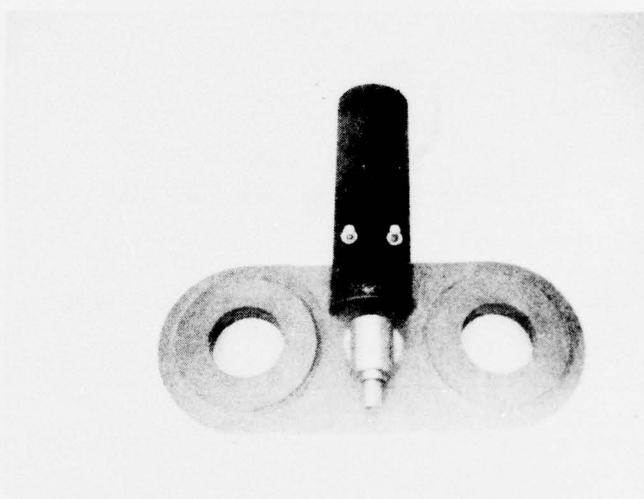

Figure A3. Tension link with connector sleeve removed.

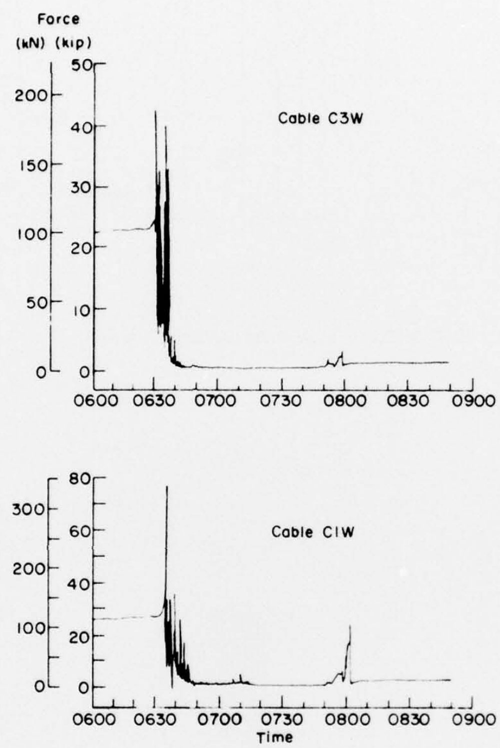

Figure A4. Sample recorder chart trace, 1 February 1976.

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